



Using Balanced Scorecard for Sustainable Design-centered Manufacturing

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Abstract

Sustainable design-centered manufacturing (SDM) will create competitive advantages for future new product development. However, selecting and balancing the indicators for economic, environmental, and social sustainability is difficult. In this research, we define the major indicators of social sustainability for development of SDM and propose a Balanced Scorecard method to evaluate the weighting factors among the three pillars and the indicators used to assess each pillar. The algorithm for the analysis is based on Structural Equation Modeling (SEM). A case, using the manufacturing data for Polylactic Acid (PLA), is developed. The results can be adapted to evaluate the performance of outcomes for new product development utilizing SDM.

Keywords: Sustainable design-centered manufacturing, Social sustainability, Balanced Scorecard, Structural Equation Modeling

1 Introduction

Waves of innovation over the last two hundred years have shifted from water power, to fossil fuel use, and may now shift from internet and information computer technology (ICT) to sustainability in the 21st century. As shown in Figure 1, Hargroves' research anticipates that the next wave of innovation will be sustainability (Hargroves, 2012). Organizations will need to incorporate sustainability into future process reengineering. We argue that the integration of design and

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manufacturing for sustainability will generate competitive advantages in the new product development process (Wang, 2012).

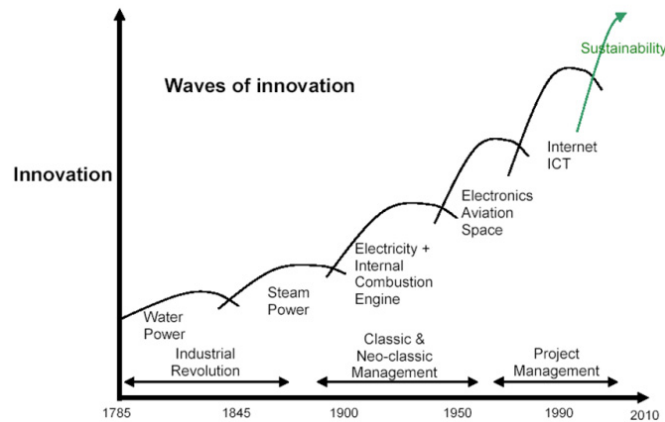


Figure 1: Waves of innovation (Hargroves, 2012)

The goal of a sustainable society includes three components. They are a flourishing economy, social health/social justice, and a sound environment. A sustainable society balances economic, social, and environmental issues as shown in Figure 2 (Diegel, 2010).

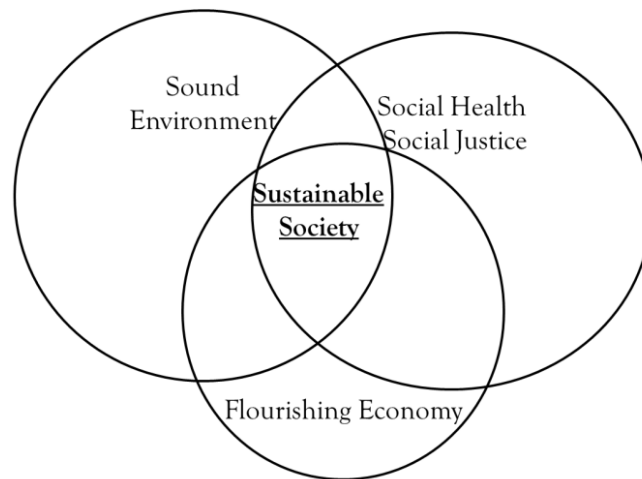


Figure 2: Components of a sustainable future (Diegel, 2010)

Sustainable design-centered manufacturing (SDM), which focuses on sustainability and develops the new manufacturing technologies for the new product design, will lead product development by using a systems approach. Figure 3 shows the shift from design for manufacturing (DFM) to SDM. As companies incorporate sustainability concepts into product design, manufacturing will overlap more completely with sustainability. The core competitive advantage of the manufacturing industry will be based on how to adopt the new concepts of sustainability and design-driven systems when developing new products.

This research develops a new Sustainable Design-centered Manufacturing (SDM) concept and proposes an algorithm by using Balanced Scorecard (BSC) for evaluation of the sustainability of a manufacturing process.

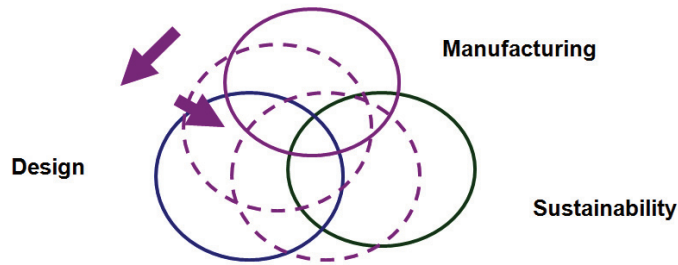


Figure 3: Trend of manufacturing for design and sustainability

2 Sustainable Design-centered Manufacturing (SDM)

In the future, product development will become a much more user-driven process. A user-driven process offers democracy of design and manufacturing through communications on websites, as well as through open intellectual properties sources. One example of a user-friendly and inexpensive manufacturing technology is additive manufacturing. Hackerspace is another example. It is one of many innovative international workspaces that attract people who are interested in design and manufacturing and who primarily develop their products at home.

Integration of new manufacturing technologies, workspaces and other innovations for design and sustainable design-centered manufacturing (SDM) generates competitive advantages for new product development in industries. Figure 4 illustrates five phases of new product development and the relationship of SDM. The basic concept of design-centered manufacturing is that research for new manufacturing technologies strives to fit advanced design needed in the beginning of the product development cycle. The synergy comes from the innovation of new product development through completely mutual communication in all phases of product design, including between design and manufacturing. Additionally, innovative manufacturing technologies are applied to fit design requirements.

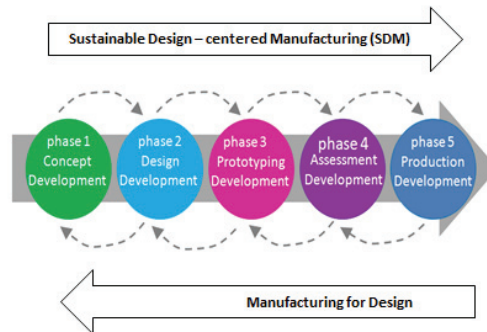


Figure 4: Five stages of different development stage

For example, Taiwan Semiconductor Manufacturing Company (TSMC), has successfully developed a model of cooperation with Altera, which designs integrated circuits, between design and manufacturing for IC chips. The model is shown in Figure 5 (Altera, 2012). TSMC plays an important role for the development of design guidelines for manufacturing in the design phase of the IC chips.

Through the new technology insertion from TSMC's manufacturing capability; integrated circuit (IC) design may change.

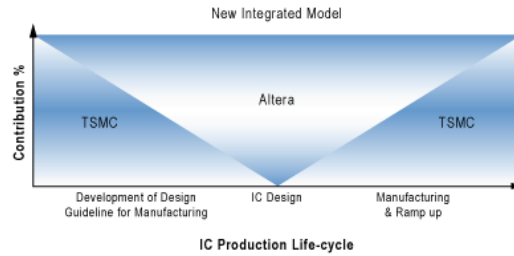


Figure 5: A new integrated model for IC production life-cycle (Altera, 2012).

Research for this paper involved analysis of four successful products and two systems to show the benefits of design-centered manufacturing. A summary of technology utilized in these products is illustrated in Table 1. Table 1 also illustrates that sustainability is reported to be a demand for plasma-gasification for waste to energy and information-based medicine for healthcare (Wang, 2012).

| Product | Demand | Technology Utilized |
|----------------------------|-----------------------|--|
| Kazuo Kawasaki Eyeglasses | Lightweight | Beta Titanium Metal Forming and Welding |
| | | Multi-Lens Molding |
| | | Physical Vaporized Deposition |
| | | Plastic Injection Modeling |
| | | Mass Customization |
| Mac iBook | Thin, Easy | PCB Frame Manufacturing |
| | | Magnesium Manufacturing Technology |
| | | User Friendly Software |
| Boeing 787-8 | Lightweight | Carbon Fiber Manufacturing |
| | | Health-Monitoring Embedded |
| | | One-Piece Fuselage |
| Integrated Circuit | Small, Fast | Chemical Etching Technology |
| | | Concurrent Engineering |
| Plasmafication | Safety Sustainable | Leachability |
| | | High Temperature Material Handling Process |
| | | Toxic Gas Handling Process |
| | | Toxic Materials Metallurgy |
| Information-Based Medicine | Safety Sustainable | Information Correlation |
| | | Automated System |
| | | Nanotechnology |

Table 1: Technology utilized for some demand products

The estimate of the increase in values of these new products and systems are depicted in Table 2. Value is the increase in price customers have been willing to pay for a product that more closely meets their needs.

| Product | Value Increased |
|----------------------------|---------------------------|
| Kazuo Kawasaki Eyeglasses | x 3 [5] |
| Mac iBook | x 2 [6] |
| Boeing 787-8 | x 1.5 [7] |
| Integrated Circuit | Beyond Moore's Law [8] |
| Plasmafication | Waste to Energy x 0.7 [9] |
| Information-Based Medicine | Human Life + 50 [10] |

Table 2: Product value added through sustainable design-centered manufacturing

3 Indicators for SDM

Selecting indicators for economic or environmental sustainability has been discussed and defined in different disciplines. The typical indicators for economic sustainability for manufacturing or production are the costs for raw materials, facilities investment, energy consumption, and profits. The environmental indicators for sustainability may include the generation of greenhouse gases (GHG), sewer or water consumption, raw material consumption or solid waste and energy consumption. However, the indicators for social sustainability are not well-defined and require further research. In the following section, we will discuss definitions and suggested indicators for social sustainability.

A thorough review of the literature on social sustainability reveals that the sustainable development agenda did not take social sustainability into account until late 1999. Sachs (1999) mentioned that a strong definition of social sustainability must rest on the basic values of equity and democracy, the latter meaning the effective appropriation of all human rights – political, civil, economic, social and cultural – by all people (Sachs, 1999). Polese and Stren (2000) stated that sustainable development is compatible with harmonious evolution of civil society, fostering an environment conducive to the compatible cohabitation of culturally and socially diverse groups while at the same time encouraging social integration, with improvements in the quality of life for all segments of the population.

Barron and Gauntlet (2002) illustrated that social sustainability occurs when the formal and informal processes, systems, structures and relationships actively support the capacity of current and future generations to create healthy and livable communities. Socially sustainable communities are equitable, diverse, connected and democratic and provide a good quality of life. Biart (2002) described that sustainability aims to determine the minimal social requirements for long-term development (sometimes called critical social capital) and to identify the challenges to the functioning of society in the long run. McKenzie (2004) defined social sustainability as: a life-enhancing condition within communities, and a process within communities that can achieve that condition.

Littig and Griessler (2005) suggested that social sustainability occurs, if work within a society and the related institutional arrangements satisfy an extended set of human needs and are shaped in a way that nature and its reproductive capabilities are preserved over a long period of time and the normative claims of social justice, human dignity and participation are fulfilled. Colantonio (2006) discussed how individuals, communities and societies live with each other and set out to achieve the objectives of development models which they have chosen for themselves, also taking into account the physical boundaries of their places and planet earth as a whole. Recently, Dixon (2012) discussed people's quality of life described as the extent to which a neighborhood supports individual and collective well-being.

Social sustainability combines design of the physical environment with a focus on how people live and use a space, related to each other and function as a community. It is enhanced by development which provides the right infrastructure to support a strong social and cultural life, opportunities for people to get involved, and scope for the place and the community to evolve (Colantonio, 2009).

| Social Sustainability Factors | References | Quantity |
|-------------------------------|---|----------|
| Health And Wellness Effects | Jawahir et al. (2006); ISO 26000 (2010); Jaafar et al. (2007); Edwards, S. (2009); Magis & Shinn (2009); Fiksel et al. (2012); Gandhi & Wang (2012); Colantonio (2009); | 8 |
| Social Justice | McKenzie (2004); Littig and Griessler (2005); USPESD (2009); Colantonio (2009); Magis & Shinn (2009); Cuthill(2010); ISO 26000 (2010) | 7 |

| | | |
|---------------------------------------|---|---|
| Operational Safety | Jawahir et al. (2006); ISO 26000 (2010); Jaafar et al. (2007); Gandhi & Wang (2012); Edwards, S. (2009) | 5 |
| Governance | McKenzie (2004); USPESD (2009); Magis & Shinn (2009); Cuthill(2010); ISO 26000 (2010) | 5 |
| Human Rights | Sachs (1999), USPESD (2009); ISO 26000 (2010); Gandhi & Wang (2012); Colantonio (2009) | 5 |
| Empowerment, Participation And Access | ISO 26000 (2010); Magis & Shinn (2009); Gandhi & Wang (2012); Colantonio (2009) | 4 |
| Social Capital | Biart[14];Cuthill(2010); Colantonio (2009);Gandhi & Wang (2012) | 4 |
| Quality Of Life | Polèse & Stren(2000);McKenzie (2004); Colantonio (2009);Littig and Griessler (2005) | 4 |
| Social Impact | Jawahir et al. (2006); Jaafar et al. (2007); Edwards, S. (2009); ISO 26000 (2010) | 4 |
| Basic Needs | Sachs (1999); Littig & Grießler (2005);Colantonio (2009) | 3 |
| Social Coherence | Polèse & Stren(2000);Littig & Grießler (2005);Colantonio (2009) | 3 |
| Transparency | Magis & Shinn (2009); ISO 26000 (2010); Gandhi & Wang (2012) | 3 |
| Ethical Responsibility | Jawahir et al. (2006); Jaafar et al. (2007) | 2 |
| Conflict Resolution | USPESD (2009); Gandhi & Wang (2012) | 2 |
| Multilateral Organizations | USPESD (2009) | 1 |
| International Treaties | USPESD (2009) | 1 |
| Global Health | USPESD (2009) | 1 |
| Appropriate Technology | USPESD (2009); ISO 26000 (2010) | 1 |

Table 3: Statistics of the social sustainable factors

To establish social sustainability indicators in this research, we assumed that the topics that were most frequently discussed in the academic literature were most important. We selected those factors for analysis using SEM. They include social justice, governance, operational safety, and health and wellness effects.

4 Balanced Scorecard for SDM

Balanced Scorecard (BSC) is a management system that fits very well with SDM processes because they both use a systems approach to management, and both consider similar factors. Bieker et al. (2001) describes BSC as a management circle of “plan-do-check-act.” BSC incorporates four areas into management consideration in an iterative process: customers, finance, internal processes, and learning and development [28]. Both SDM (as described in Figure 4) and BSC utilize iterative processes, another reason the two processes work well together.

Options for assessing SDM processes include commercial software to analyze the effects between economic and environmental pillars. Some comprehensive life cycle assessment tools are listed in Table 4. These tools can be used to evaluate resource usage and environmental impacts that are related to a certain material, product, manufacturing process, transportation, and end-of-life treatment. These tools may be appropriate for evaluation in highly complex manufacturing processes. However, the data input for the analysis determine the quality of outcomes after model simulation (garbage-in/garbage out).

| Software | Country | Developer |
|---|-------------|--|
| BEES 4 | USA | NIST (National Institute of Standards and Technology) Engineering Laboratory |
| Sustainable Minds | USA | Sustainable Minds, LLC |
| Economic Input-Output Life Cycle Assessment | USA | GREEN DESIGN INSTITUTE -Carnegie Mellon University |
| GREET Model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) | USA | Argonne National Laboratory |
| COMPASS– Comparative Packaging Assessment | USA | GreenBlue |
| LCAPIX 2 | USA | KM Limited |
| CMLCA | USA | Leiden University |
| The Boustead Model | UK | Boustead Consulting Ltd. |
| Quantis Suite 2.0 | Switzerland | Quantis |
| SimaPro 8 | Netherlands | PRé Consultants |
| ECO-it 1.3 | Netherlands | PRé Consultants |
| IDEMAT | Netherlands | Delft University of Technology (TU Delft) |
| GaBi 6 | Germany | PE International GmbH |
| GEMIS (Global Emission Model for Integrated Systems) | Germany | The International Institute for Sustainability Analysis and Strategy (IINAS) |
| Umberto 5 | Germany | ifu Hamburg GmbH |
| openLCA | Germany | GreenDelta GmbH |
| TEAM 5 | France | Ecobilan - PricewaterhouseCoopers |
| WISARD | France | Ecobilan - PricewaterhouseCoopers |
| SULCA 4.2 | Finland | VTT |
| The Environmental Impact Estimator | Canada | The ATHENA™ Sustainable Materials Institute |

Table 4: Comprehensive List of Life-Cycle Assessment Tools

Another option is to build a model by using system dynamics or computer simulation of the scenarios to forecast results. However, these complex systems are based on assumptions that may not apply and may not have consistent or reliable results.

This research proposes a Structure Equation Modeling (SEM) method, which uses iteration algorithms of regressions and correlations between indicators to decide the weighting factors in these systems. One possible structure of SEM for SDM is shown below in Figure 6.

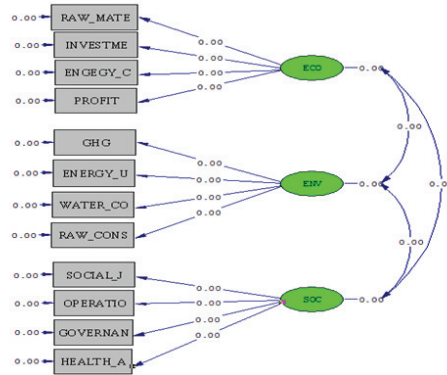


Figure 6: The structure of SEM for SDM

5 Case Study for Polylactic Acid Manufacturing

Based on research conducted by Vink et al. (2007& 2010), the most important environmental factors include land use, nonrenewable energy, greenhouse gas emission, and water consumption. NatureWorks (2009), the largest producer of PLA in the world, changed its product design to SDM and tracked its use of the factors recommended by Vink and his colleagues. Table 5 and Table 6 give environmental and economic factors for the two generations of PLA polymers. These factors are standardized to 1 kg PLA as the basis of conducting a cradle-to-gate analysis. The table illustrates that reductions occurred in nonrenewable energy use and in GHG emissions.

| | |
|---|--|
| Land use (before 2009) | 1.69 m ² /kg PLA (Vink <i>et al</i> , 2007) |
| Land use after 2009 | 1.72 m ² /kg PLA (Vink <i>et al</i> , 2010) |
| Nonrenewable energy use (prior to 2009) | 50 MJ/kg PLA (Vink <i>et al</i> , 2007) |
| Nonrenewable energy use | 42 MJ/kg PLA (Vink <i>et al</i> , 2010) |
| Greenhouse gas emissions (before 2009) | 2 kg/kg PLA (Vink, 2007) |
| Greenhouse gas emissions | 1.3 kg/kg PLA (Vink <i>et al</i> , 2010) |
| Water consumption (prior to 2009) | 48.79 kg/kg PLA (Vink, 2007) |
| Water consumption | 69.02 kg/kg PLA(Vink <i>et al</i> , 2010) |

Table 5: Data Sources for Environmental Factors

Pelsoci (2007) demonstrates that the NatureWorks' production capacity from 2003 to 2017 (Table 7) reflects the achievement of full production capacity in 2011. These factors use manufacturing 1 kg PLA as the basis, and present multiple PLA production capacity per year. These data are used to develop analysis models.

| | |
|--------------------------------------|--|
| Cost of PLA Production | 1.97-2.42 USD per kg PLA (Shen, <i>et al</i> , 2009; Chiarakorn, <i>et al</i> , 2011) |
| Price of PLA | 3.04-4.69 USD per kg PLA (Shen, 2009, <i>et al</i> .; Chiarakorn, <i>et al</i> , 2011) |
| The Capital Investment Cost | \$300 million USD (Shen, <i>et al</i> , 2009) |
| Average O&M Cost | 4% of investment cost (Dornburg, 2006) |
| Average Land Cost in Blair, Nebraska | \$1,766 USD per acre 9(Johnson, <i>et al</i> , 2001) |
| Plant area | 640 acres (Nature Works, 2014) |
| Land cost | \$1,130,240.00 USD (Khalid, 2011; Johnson, <i>et al</i> , 2001) |
| Corn (Raw Material Use) | 2.5 kg corn per kg PLA (Khalid, 2011) |
| Average Price of Corn from 2001-2012 | \$0.134 per kg corn (Corn Trade, 2014) |

Table 6: Data Sources for Economic Factors

| Year | PLA Production Capacity (ton) |
|------|-------------------------------|
| 2003 | 4,535 |
| 2004 | 13,605 |
| 2005 | 27,210 |
| 2006 | 54,420 |
| 2007 | 65,304 |
| 2008 | 78,456 |
| 2009 | 94,328 |
| 2010 | 113,375 |
| 2011 | 136,050 |
| 2012 | 136,050 |
| 2013 | 136,050 |
| 2014 | 136,050 |
| 2015 | 136,050 |
| 2016 | 136,050 |
| 2017 | 136,050 |

Table 7: PLA Production Capacity (Nature Works, 2014)

Table 8 presents complete environmental factors in the PLA manufacturing process based on literature reviews from Table 6. These factors use manufacturing 1 kg PLA as the basis, and present multiple PLA production capacity per year. These data are also used to develop analysis models.

| Year | GHG (Million kg CO ₂ eq.) | Energy Use (Million MJ) | Water Consumption (Million ton) | Raw Material Use (Million kg) |
|------|--------------------------------------|-------------------------|---------------------------------|-------------------------------|
| 2003 | 9 | 196 | 221 | 11 |
| 2004 | 27 | 588 | 664 | 34 |
| 2005 | 54 | 1,177 | 1,328 | 68 |
| 2006 | 109 | 2,353 | 2,655 | 136 |
| 2007 | 131 | 2,824 | 3,186 | 163 |
| 2008 | 157 | 3,392 | 3,828 | 196 |
| 2009 | 123 | 4,079 | 6,511 | 236 |
| 2010 | 147 | 4,902 | 7,825 | 283 |
| 2011 | 177 | 5,883 | 9,390 | 340 |
| 2012 | 177 | 5,883 | 9,390 | 340 |
| 2013 | 177 | 5,883 | 9,390 | 340 |
| 2014 | 177 | 5,883 | 9,390 | 340 |
| 2015 | 177 | 5,883 | 9,390 | 340 |
| 2016 | 177 | 5,883 | 9,390 | 340 |
| 2017 | 177 | 5,883 | 9,390 | 340 |

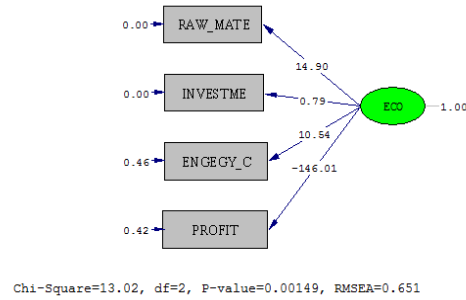
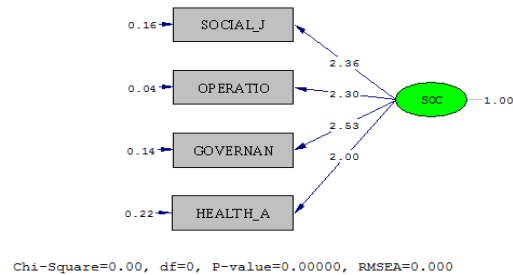
Table 8: Complete Environmental Factors from 2003 to 2017

The rankings between social factors and PLA production capacity reflect social justice, operation safety, governance, and health and wellness effects. With the 140,000 full production capacity of the PLA plant, the percentage of different capacity utilization is shown in Table 9. According to the rankings between social factors and the percentage of PLA production utilization, Table 9 illustrates the level of importance for social sustainability factors.

| Production Capacity (ton) | Production Capacity (%) | Social Justice | Operational Safety | Governance | Health and Wellness Effects |
|------------------------------|----------------------------|----------------|--------------------|------------|-----------------------------|
| 4,535 | 3% | 3 | 2 | 2 | 1 |
| 13,605 | 10% | 3 | 3 | 2 | 2 |
| 27,210 | 19% | 4 | 3 | 3 | 3 |
| 54,420 | 39% | 5 | 4 | 3 | 4 |
| 65,304 | 47% | 5 | 4 | 3 | 4 |
| 78,456 | 56% | 6 | 4 | 4 | 5 |
| 94,328 | 67% | 8 | 6 | 5 | 5 |
| 113,375 | 81% | 8 | 7 | 7 | 6 |
| 136,050 | 97% | 9 | 8 | 8 | 7 |

Table 9: Level of Importance for Social Sustainability Factors

After running an SEM regression using LISREL, weighting factors for economic and social sustainability were obtained, but weighting factors for environmental sustainability could not be validly produced with the data used in this research. The weighting factors for economic and social sustainability are shown in Figure 7 and Figure 8 separately.

**Figure 7:** The weighting factors for economic sustainability**Figure 8:** The weighting factors for social sustainability

Since the sampling size is 16 and is not sufficient to verify the robustness of the SEM model, these results offer a new methodology for the further analysis. Once the sufficient data can be forecast or obtained in advance, the model will be more useful for evaluation of the manufacturing process.

6 Conclusion and Future Works

This research discusses the trend of SDM and develops a performance evaluation method for use of SDM. In this paper data from production of PLA was input to develop an SEM model using LISREL. The Balanced Scorecard system of management was used to structure the interrelationships of the constructs economic sustainability, environmental sustainability and social justice used in the SEM model. LISREL software ran regression analysis, which provided the weighting factors for the selected indicators among economic, and social sustainability. Weighting factors could not be validly obtained for environmental sustainability with the database used for this research. The database used in this paper is insufficient for incorporation into a Balanced Scorecard method because the data to assess environmental factors was insufficient. However, this systems approach is capable of incorporating large amounts of varying data, and with sufficient data, can be used as a solution to help industries balance the indicators for sustainable development in SDM.

If we have sufficient statistical data to construct a SEM model and to determine the weighting of main factors selected in the scorecard for economic, environmental, and social sustainability, then the weighting of each factor determines the rules for the prioritization for strategic planning and resources allocation of this manufacturing process. This algorithm can balance the selected factors for SDM process and help the performance evaluation of the process. We could apply this balanced SDM process from design phase of product development in the future.

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